II.A.2. ARE THERE BIOGEOPHYSICAL LIMITS TO GROWTH?

Summary

In this section we consider possible biogeophysical limits to continued output growth.

In II.A.2.a we evaluate limits imposed by scarce energy resources. We conclude that a "moderate techno-optimist" might judge that world energy use can continue to grow at rates of about 1% per year for perhaps 400 to 600 years, until it reaches an indefinitely sustainable level 20 times today's level, while a "moderate techno-skeptic" might judge that energy use can grow at these rates for maybe 100 to 270 years, until it reaches an indefinitely sustainable level perhaps 5 times as high as today's. This exercise suggests that the value of 30 terawatts (about 3 times today's level) that we used as the practicable upper bound in our ideal scenario, Scenario 5, may be unnecessarily conservative.

In II.A.2.b Nordhaus' DICE model is used to estimate the costs of avoiding catastrophic climate change. This exercise suggests that it should be possible to make a transition to a non-fossil fuel world over the next century while maintaining net positive rates of economic growth.

In II.A.2.c we comment briefly on entropic degradation and human appropriation of biomass as limits to growth.

Section II.A.2.d reviews studies using large scale integrated assessment models of global change. At present these studies do not give evidence that biogeophysical factors constitute limits to continued economic growth. However, most of the global integrated assessment models assume, exogenously, that economic growth will slow, quite dramatically, over the coming century. Formally this is expressed as a decline in the productivity growth rate, or in the growth rate of productivity-enhancing technological innovation. The possibility of limits to growth imposed by limits to technological innovation is discussed in Section II.B.

II.A.2. ARE THERE BIOGEOPHYSICAL LIMITS TO GROWTH?

Introduction

BOX IIA-12 lists resource and environmental problems associated with increasing human activity. How long can we continue to lose topsoil, pollute the ocean, encroach upon arable land or erode the ozone layer, before we breach some critical ecological threshold and irreparably damage the life-support systems of our planet?

Ecologists commonly distinguish two categories of natural resource limits: stock limits and sink limits. Stock limits are reached when a finite resource is exhausted, given available technology. Sink limits are reached when the waste products of resource use exceed the ability of natural or technological systems to prevent them from causing unacceptable harm.

In this section I focus on two instances of possible biogeophysical limits. As an important example of stock limits I focus on energy resources. Energy is important because there are no substitutes for it and because many other resource shortages can be alleviated if sufficient energy is available. As an important example of the possibility of catastrophic impacts caused when sink limits are exceeded, I focus on global warming. I comment briefly on entropic degradation and the human appropriation of biomass as limits to growth. I comment also on the results of large scale integrated assessment models concerning biogeophysical limits to growth.

II.A.2.a. Limits to the Growth of Energy Use

In this exercise we estimate the length of time over which energy use can continue to grow, and the length of time over which a constant level of energy use can thereafter be sustained, under several scenarios. We use annual rates of 0.5%, 1.0% and 1.5% for scenarios of slow, medium and fast energy growth.[1] **IIA-13** shows how these energy use growth rates can

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[1] These values approximate the range of forecasts of the growth rate of energy use over the coming century used in many studies (e.g., IPCC 1994.)

BOX IIA-12. ENVIRONMENTAL CONCERNS
[sources: Ekins et al. (1992), Easterbrook (1995), Ausubel et al (1995)]

climate change/global warming
sea level rise
ozone layer depletion
biodiversity loss; species extinction; overfishing
deforestation; clearcutting; stripmining
wilderness loss
wetlands degradation
large dam construction; river siltation
land fills
coastal development
soil erosion; topsoil loss; overgrazing; desertification
acid rain
pesticide overuse
fossil fuel pollution; urban air pollution
marine and water pollution; oil spills
nuclear and chemical accidents
hazardous waste disposal and materials use
indoor radiation

BOX IIA-13. GROWTH RATES OF ENERGY EFFICIENCY, ENERGY USE AND OUTPUT

		total energy use growth (% per year)			
		0.0	0.5	1.0	1.5
energy efficiency growth (% per year)	0	0.0	0.5	1.0	1.5
	0.5	0.5	1.0	1.5	2.0
	1.0	1.0	1.5	2.0	2.5
	1.5	1.5	2.0	2.5	3.0

The table shows the combinations of improvements in energy efficiency and growth of energy use that can support different levels of total output growth, shown as the values in the squares. Thus GDP can grow at an annual rate of 2% if total energy use increases at 1.5% and efficiency increase at .5%, or if total energy use increases at .5% while efficiency increases at 1.5%. If energy use is kept at a constant level GDP can increase at the rate at which efficiency increases.

combine with improvements in energy efficiency (GDP/energy) to support varying growth rates of output (GDP).[2]

Procedure

Our first step is to estimate the total stock of non-renewable energy sources and the maximum practicable flows of renewable energy resources.

Our second step is to quantify the biogeophysical limits on the growth of energy use. For this exercise we focus on two important biogeophysical limits. One is atmospheric warming, which can result from either growing concentrations of greenhouse gases or from thermal pollution. The other is the availability of land.

Our third step is to use these estimates to construct credible scenarios of energy use over time.

Stocks and Flows of Energy Resources

Tables 1, 2 and 3 in **Box IIA-14** show the availability of stocks and flows of various energy resources as estimated in studies by different authors. Details of these studies are shown in Appendix 6. I used the results of these studies to choose the stock and flow values used in this exercise, shown in Table 4.

Biogeophysical constraints

The important biogeophysical constraint on the use of fossil and nuclear fuels, other than stock constraints, is global atmospheric warming. The important biogeophysical constraint on photovoltaic hydrogen and biomass is the availability of land.[3]

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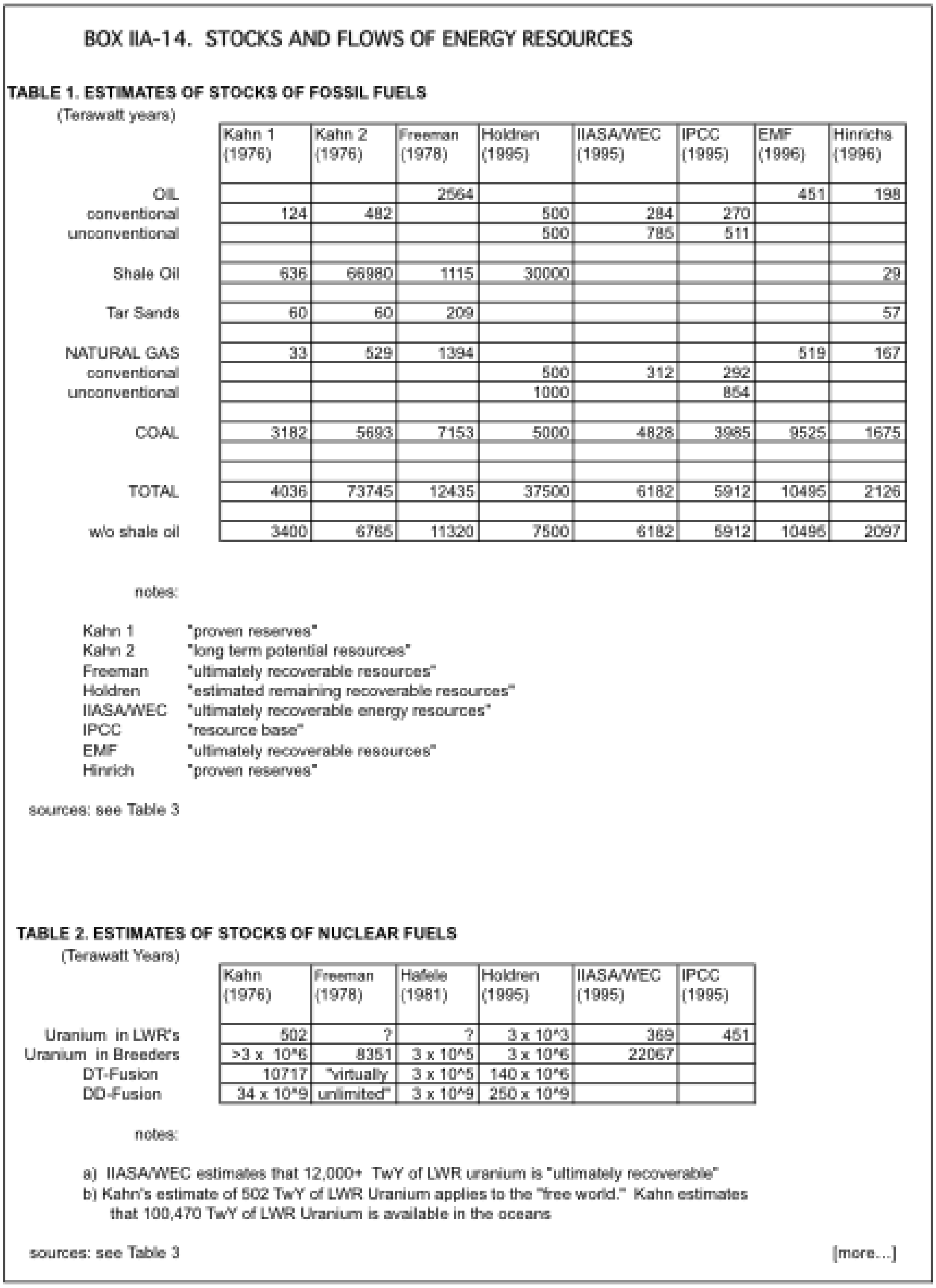
[2] Consider a scenario that shows energy use increasing at 1% a year for 75 years, ceasing to grow at that time but continuing indefinitely at the level reached at that time. If energy efficiency increases indefinitely at 0.5% per year, then conventional output could increase at 1.5% for 75 years and 0.5% thereafter.

[3] Nuclear reactions and fossil fuel combustion liberate energy tied up in nuclear and chemical bonds, and thus add heat to the atmosphere. Solar energy systems collect and change the radiant energy of sunlight into new forms, but add no new heat to the atmosphere. However, solar energy systems require large land areas in order to usefully concentrate diffuse radiant energy.



BOX IIA-14. STOCKS AND FLOWS OF ENERGY RESOURCES

TABLE 1. ESTIMATES OF STOCKS OF FOSSIL FUELS

(Terawatt years)

	Kahn 1 (1976)	Kahn 2 (1976)	Freeman (1978)	Holdren (1995)	IIASA/WEC (1995)	IPCC (1995)	EMF (1996)	Hinrichs (1996)
OIL			2564				451	198
conventional	124	482		500	284	270		
unconventional				500	785	511		
Shale Oil	636	66980	1115	30000				29
Tar Sands	60	60	209					57
NATURAL GAS	33	529	1394				519	167
conventional				500	312	292		
unconventional				1000		854		
COAL	3182	5693	7153	5000	4828	3985	9525	1675
TOTAL	4036	73745	12435	37500	6182	5912	10495	2126
w/o shale oil	3400	6765	11320	7500	6182	5912	10495	2097

notes:

Kahn 1	"proven reserves"
Kahn 2	"long term potential resources"
Freeman	"ultimately recoverable resources"
Holdren	"estimated remaining recoverable resources"
IIASA/WEC	"ultimately recoverable energy resources"
IPCC	"resource base"
EMF	"ultimately recoverable resources"
Hinrich	"proven reserves"

sources: see Table 3

TABLE 2. ESTIMATES OF STOCKS OF NUCLEAR FUELS

(Terawatt Years)

	Kahn (1976)	Freeman (1978)	Hafele (1981)	Holdren (1995)	IIASA/WEC (1995)	IPCC (1995)
Uranium in LWR's	502	?	?	3 x 10^3	369	451
Uranium in Breeders	>3 x 10^6	8351	3 x 10^5	3 x 10^6	22067	
DT-Fusion	10717	"virtually	3 x 10^5	140 x 10^6		
DD-Fusion	34 x 10^9	unlimited"	3 x 10^9	250 x 10^9		

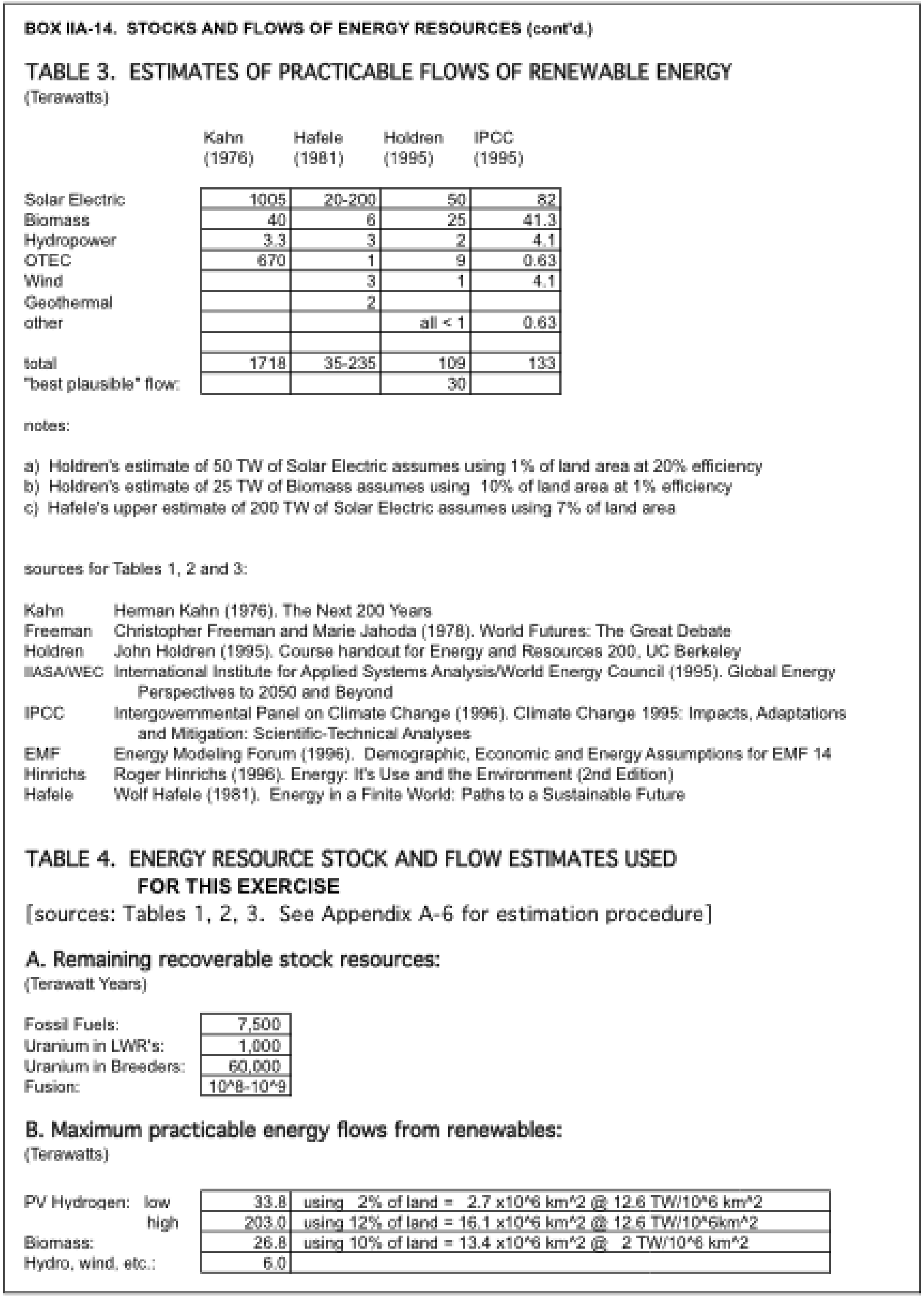
notes:

a) IIASA/WEC estimates that 12,000+ TwY of LWR uranium is "ultimately recoverable"

b) Kahn's estimate of 502 TwY of LWR Uranium applies to the "free world." Kahn estimates that 100,470 TwY of LWR Uranium is available in the oceans

sources: see Table 3

[more...]



BOX IIA-14. STOCKS AND FLOWS OF ENERGY RESOURCES (cont'd.)

TABLE 3. ESTIMATES OF PRACTICABLE FLOWS OF RENEWABLE ENERGY

(Terawatts)

	Kahn (1976)	Hafele (1981)	Holdren (1995)	IPCC (1995)
Solar Electric	1005	20-200	50	82
Biomass	40	6	25	41.3
Hydropower	3.3	3	2	4.1
OTEC	670	1	9	0.63
Wind		3	1	4.1
Geothermal		2		
other			all < 1	0.63
total	1718	35-235	109	133
"best plausible" flow:			30	

notes:

a) Holdren's estimate of 50 TW of Solar Electric assumes using 1% of land area at 20% efficiency
b) Holdren's estimate of 25 TW of Biomass assumes using 10% of land area at 1% efficiency
c) Hafele's upper estimate of 200 TW of Solar Electric assumes using 7% of land area

sources for Tables 1, 2 and 3:

Kahn	Herman Kahn (1976). The Next 200 Years
Freeman	Christopher Freeman and Marie Jahoda (1978). World Futures: The Great Debate
Holdren	John Holdren (1995). Course handout for Energy and Resources 200, UC Berkeley
IIASA/WEC	International Institute for Applied Systems Analysis/World Energy Council (1995). Global Energy Perspectives to 2050 and Beyond
IPCC	Intergovernmental Panel on Climate Change (1996). Climate Change 1995: Impacts, Adaptations and Mitigation: Scientific-Technical Analyses
EMF	Energy Modeling Forum (1996). Demographic, Economic and Energy Assumptions for EMF 14
Hinrichs	Roger Hinrichs (1996). Energy: It's Use and the Environment (2nd Edition)
Hafele	Wolf Hafele (1981). Energy in a Finite World: Paths to a Sustainable Future

TABLE 4. ENERGY RESOURCE STOCK AND FLOW ESTIMATES USED FOR THIS EXERCISE

[sources: Tables 1, 2, 3. See Appendix A-6 for estimation procedure]

A. Remaining recoverable stock resources:

(Terawatt Years)

Fossil Fuels:	7,500
Uranium in LWR's:	1,000
Uranium in Breeders:	60,000
Fusion:	10^8-10^9

B. Maximum practicable energy flows from renewables:

(Terawatts)

PV Hydrogen:	low	33.8	using 2% of land = 2.7 x10^6 km^2 @ 12.6 TW/10^6 km^2
	high	203.0	using 12% of land = 16.1 x10^6 km^2 @ 12.6 TW/10^6km^2
Biomass:		26.8	using 10% of land = 13.4 x10^6 km^2 @ 2 TW/10^6 km^2
Hydro, wind, etc.:		6.0	

1. Atmospheric warming: Most current estimates of the cost of damages that might follow a 2.5°C warming range from 1 to 4 percent of GDP. No mechanisms have yet been identified which suggest that a 2.5°C warming might precipitate a catastrophe that would bring economic growth to an end. However, as temperatures rise above 2.5°C the possibility of catastrophe does also, as discussed further in Section II.A.2.b. In the absence of firmer data I choose a figure of 4° C as the level of atmospheric warming that would likely produce impacts severe enough to bring economic growth to an end. If we add a precautionary margin of 10% we get a final value of 3.6°C as the level of atmospheric warming that humankind would probably agree with near unanimity should be avoided.[4]

Atmospheric warming above pre-industrial levels can be caused by increased concentrations of greenhouse gases or by thermal pollution.

***a. Warming due to increased concentrations of greenhouse gases*:** A variety of greenhouse gas emissions scenarios exist that prevent warming from exceeding 3.6 °C, as shown in **IIA-15.** One might be for emissions to decline and stabilize at 6 GtC by 2025. Another would allow emissions to increase to 11 GtC by 2025, but decline within the next quarter century to 5.5 GtC. A third would stabilize emissions at 11 GtC from 2025 to 2050, but require reduction to 4.5 GtC by 2075.[5] The amount of coal that produces emissions of 6 GtC can produce about 9 TW of energy. For the remainder of this exercise we'll regard 9 TW as the biogeophysical limit on the production of energy from fossil fuels.

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[4] The economic rationale is that if a 3.5°C warming runs a strong risk of bringing economic growth to an end, it is very unlikely that if 3.5 °C is exceeded anybody can ever again be made better off, without making someone else worse off.

[5] These scenarios were generated using an extended version of the global warming model developed by Cline (1992), which I prepared for my master's thesis (R. Hayes 1996). The extended Cline model is described in Appendix 7. Note that the sooner that emissions begin to be curtailed, the higher the stable level of acceptable carbon emissions allowable afterwards will be.

BOX IIA-15. Avoiding a 3.6 degree warming

Figure 1. Emissions Scenarios That Avoid A 3.6 Degree Warming

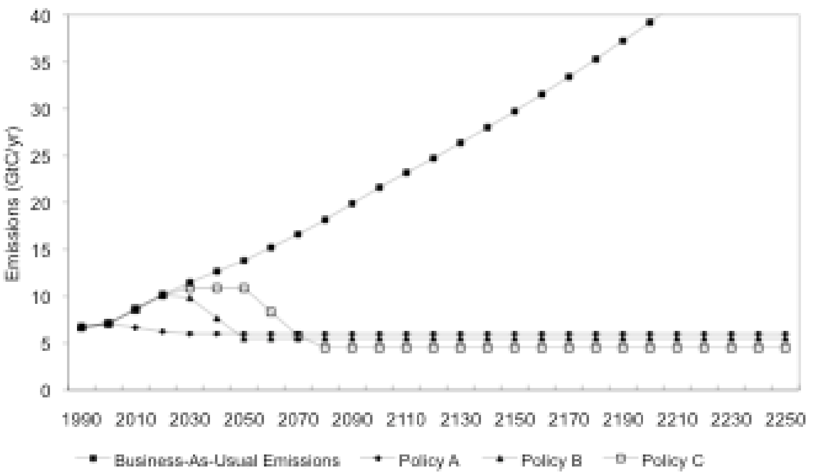
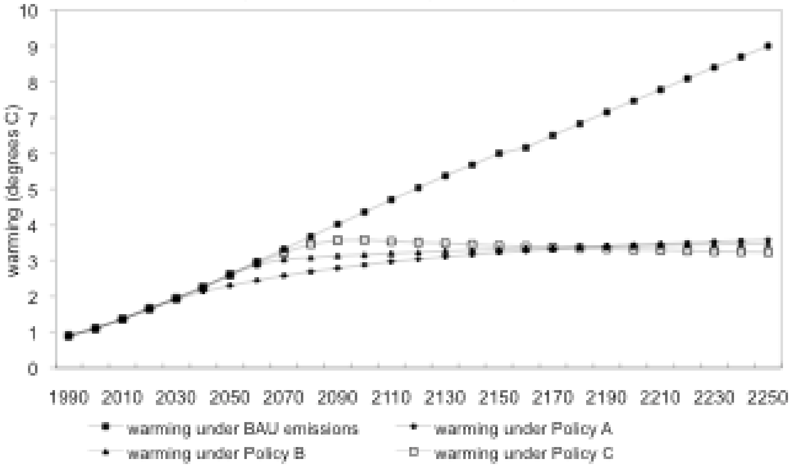


Figure 2. Global Warming < 3.6 Degrees



Emissions Policy Descriptions:

Business-As-Usual: This follows the BAU scenario of Cline (1992)
Policy A: Global emissions begin declining in 2000 and stabilize at 6 GtC by 2025
Policy B: Emissions follow BAU projections until they reach 11 GtC in 2025, then begin declining until they reach and stabilize at 5.5 GtC
Policy C: Emissions follow BAU projections until the reach 11 GtC in 2025, stabilize at that level for 25 years, then decline and stabilize at 4.5 GtC by 2075

b. Warming due to thermal pollution: **Box IIA-16** shows that a global warming of 3.6ºC could be produced by thermal pollution if total energy use grew to 5400 TW. This is 490 times the current level of 11 TW.

2. Available Land

For purposes of this exercise we assume that 2% of ice-free land is currently suitable and available for the production of photovoltaic hydrogen. In addition we suggest that over periods of a century or longer 12% of ice-free land could be used. **IIA-17** shows the global distribution of ecosystem types and includes speculative estimates of the land area of each of these that might be devoted to photovoltaic hydrogen.[6]

SCENARIOS

Given the available stocks and flows of energy resources that we're calculated, and the limited ability of the earth's ecosystems to sustain global warming or conversion of land to energy production, how long can energy use continue to grow at 0.5, 1.0, and 1.5 percent?[7]

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[6] In this exercise I've made the simplifying assumption that biomass will not serve as a major energy source if fusion or photovoltaic hydrogen are practicable. The purpose of this exercise is to see how long energy use can grow before reaching stock or sink limits. The presumption is that energy growth of this magnitude is desired in order to support a high-tech, industrial world, and fusion or photovoltaic hydrogen are high-tech, industrial enterprises. Biomass energy production is in comparison low-tech. We assume here that biomass would be available as a bridge or fall-back source of energy, but would not form the core of a global energy regime. In any event, if biomass were given a greater role the time over which energy could be expected to grow, or be sustained, would be moderately greater than the figures shown in this exercise. On the other hand, if neither fission nor photovoltaic hydrogen are practicable, biomass could be an extremely important energy source.

[7] The formulas used to construct the scenarios are:

1. To calculate the level of energy use E if it grew at rate r for t years: $E_t = E_0 e^{rt}$
2. To calculate the total amount Q of a depletable energy resource consumed if its use E grew at rate r for t years: $Q_t = \int_0^t E_0 e^{rt} = \frac{E_0}{r}\left(e^{rt} - 1\right)$
3. To calculate the time T it would take to exhaust a depletable energy resources stock Q if its initial rate of use is E_0 and it grew at rate r: $T = \frac{1}{r}\ln\left(\frac{rQ}{E_0} + 1\right)$

BOX IIA-16. THERMAL POLLUTION

When energy is used to do work it generates heat. The more energy that people use, the more heat is released into the earth's atmosphere. The earth's atmosphere absorbs heat from a variety of sources and releases heat into empty space, as shown in the basic energy balance equation,

$$(1) \qquad -\pi R_E^2 S + (M + M_m) = \pi R_E^2 SA + 4\pi R_E^2 \varepsilon\sigma T^4$$

where:

S	solar constant	0.135 watts/cm^2
R_E	radius of the earth	$6.37\text{x}10^8$ cm
A	albedo	0.37
ε	emissivity	0.55
σ	Stephan-Boltzman constant	$5.67\text{x}10^{-12}$ watts/cm^2 ^{0}K^4
M	misc. natural energy inputs	$27\text{x}10^{12}$ watts (volcanoes, etc.)
M_m	anthropogenic energy inputs	$11\text{x}10^{12}$ watts (1995; fossil & nuclear fuel use)

This equation can be used to calculate the amount by which the atmosphere will warm as a result of any level of human energy use (M_m). We manipulate (1) to get:

$$(2) \qquad T_1 = [\,((1\text{-}A)\,\pi R_E^2 S + M\,) / \,(4\pi R_E^2 \varepsilon\,\sigma\,)\,]^{1/4}$$

where T_1 is the temperature of the atmosphere in the absence of anthropogenic energy inputs (i.e., when $M_m = 0$). Using the constant and parameter values given above we find that $T_1 = 288^0\,K = 15^0\,C = 59^0\,F$. Following Holdren (1971) we note that for small changes in M_m,

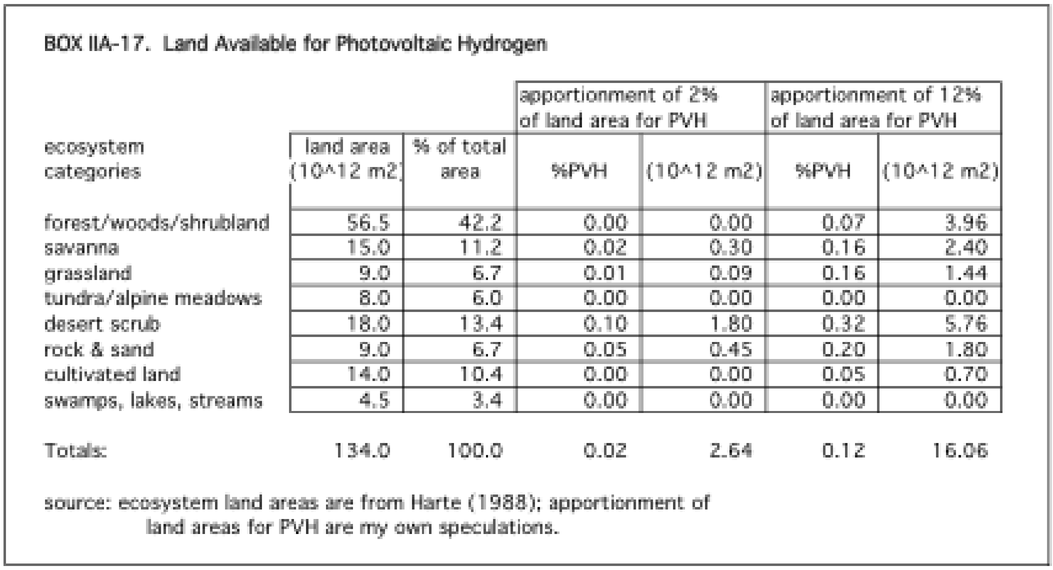
$$(3) \qquad T_2 - T_1 \sim \Delta T << T_1 = 288^0\,K$$

We can manipulate the equations and apply given values to get:

$$(4) \qquad \Delta T = .25 M_m T_1\,[(1\text{-}A)\,4\pi R_E^2\,S]^{-1} = 6.67\text{x}10^{-16}\,M_m$$

This expression allows us to generate the table below showing the atmospheric warming generated by higher levels of human energy use:

human energy use (TW)	anthropogenic warming (^{0}C)	date reached; or years until it is reached with 1% and 5% energy use growth rates	
5	.0033	1970 - historical	
10	.0067	1992 - historical	
30	.0200	2035 - reference scenario	
100	.0670	2108 - reference scenario	
500	.3300	380 yrs (1%)	760 yrs (.5%)
1000	.6670	450 yrs (1%)	900 yrs (.5%)
2000	1.33	520 yrs (1%)	1030 yrs (.5%)
3750	2.5	580 yrs (1%)	1160 yrs (.5%)
5400	3.6	620 yrs (1%)	1230 yrs (.5%)



BOX IIA-17. Land Available for Photovoltaic Hydrogen

ecosystem categories	land area (10^12 m2)	% of total area	apportionment of 2% of land area for PVH %PVH	 (10^12 m2)	apportionment of 12% of land area for PVH %PVH	 (10^12 m2)
forest/woods/shrubland	56.5	42.2	0.00	0.00	0.07	3.96
savanna	15.0	11.2	0.02	0.30	0.16	2.40
grassland	9.0	6.7	0.01	0.09	0.16	1.44
tundra/alpine meadows	8.0	6.0	0.00	0.00	0.00	0.00
desert scrub	18.0	13.4	0.10	1.80	0.32	5.76
rock & sand	9.0	6.7	0.05	0.45	0.20	1.80
cultivated land	14.0	10.4	0.00	0.00	0.05	0.70
swamps, lakes, streams	4.5	3.4	0.00	0.00	0.00	0.00
Totals:	134.0	100.0	0.02	2.64	0.12	16.06

source: ecosystem land areas are from Harte (1988); apportionment of land areas for PVH are my own speculations.

1. Fossil fuels

If global warming were not a concern then the available 7500 TWy of fossil fuels would allow energy use to grow at 0.5%, 1.0% and 1.5% for another 271, 191 and 151 years, respectively. At those times total energy use would have grown to 50 TW, 87 TW, or 123 TW, which represent levels of use 3.9, 6.7 and 9.5 times the year 2000 rate of 13 TW. After these dates new energy sources would need to be available in order to avoid a global crash of the sort forecast by the World 3 reference scenario.

However, we've seen that fossil fuels cannot supply more than 9 TW on a long term basis without causing global warming to exceed our 3.6ºC limit. If we take 9 TW as the effective sustainable level of fossil fuel use, we see that the stock of 7500 TWy would last for 833 years.

2. Fossil fuels plus light water reactor fission

If we chose to rely heavily on LWR fission, energy use could grow at 0.5, 1.0 and 1.5 percents beyond 2000 for another 162, 125 and 104 years. Together with the 9 TW of sustainable fossil fuel energy, total energy use at these dates would be 18, 23 and 28 TW. However, all uranium fuel would have been exhausted, and new energy sources would need to have been developed if we wish to avoid a return to a 9 TW world.

3. Fossil fuels plus breeder reactors

If we use the available supply of uranium for breeders rather than for fission we would have a total of 67,500 TWy of power available. At rates of 0.5%, 1.0% and 1.5% energy use could grow for 659, 397 and 294 years, reaching total use levels of 351, 689 and 1069 TW, which are 27, 53 and 82 times the 2000 level of 13 TW. At the end of these growth periods alternative sources would be needed if catastrophic collapse is to be avoided.

4. Fusion

If fusion turns out to be a feasible and practicable energy source within the next 50 years or so then the lower estimate of 10^8 TWy of available power would allow growth at 0.5% 1.0% and 1.5% for 1958 years, 1048 years and 756 years, reaching total use levels of .5 million, 1 million and 1.5 million TW. (Here we assume that fusion begins as a commercial power source in 2050, after total energy use has grown at 1.5% per year to 28 TW.)

Of course, these levels are orders of magnitude above the limit of 5400 TW that we determined earlier would be necessary to avoid a global warming greater than 3.6 ^{o}C due to thermal pollution. If we begin in 2050 at 28 TW, energy use supplied by fusion power can increase at 0.5%, 1.0% and 1.5% for 1052, 526, and 351 years before reaching the 5400 TW limit.

After the 5400 TW limit is reached energy use growth will have to end. However, the stock of fusion energy resources would not be exhausted at that time.[8] Using the middle scenario in which an energy use level of 28 TW increases at 1% for 526 years beyond 2050, we find that 537,000 TWy of fusion resources will have been used over that period, with 10^8 - 5.37x10^5 = 99.5x10^6 TWy remaining. At a constant annual rate of use of 5400 TW this stock will last for about 184,000 years. If the higher 10^9 TWy estimate of fusion resources is used a 5400 TW level of energy use can be sustained for 1.8 million years.

5. Photovoltaic Hydrogen

What if we find out that fusion is not a practicable energy source? Photovoltaic hydrogen is an alternative. Thermal pollution is not a constraint on the increasing use of photovoltaic hydrogen, but land use is.

If energy use grows at 0.5%, 1.0% or 1.5% between 2000 and 2050 total energy use will have grown to 17, 21 or 28 TW over that time. For the following exercise we assume that these levels can be supplied at a constant level for a certain period thereafter (see below) by fossil fuels (9 TW), other renewables (5 TW), and nuclear power (3, 7 or 14 TW). [9]

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[8] Fossil and nuclear fuels, by contrast, reach their limits by exhaustion.

[9] These values are typical of the low, medium and high values of nuclear power use projected for 2050 by many analysts.

If photovoltaic hydrogen becomes available by 2050, how much longer will energy use be able to continue to grow? If we use the lower limit of 2% land availability for photovoltaic hydrogen, we see that energy use can grow at 0.5%, 1.0% or 1.5% for 269, 146 or 103 years beyond 2000. At these times total energy use will be between 51, 55 or 62 TW.

If we use the upper limit of 12% land availability for photovoltaic hydrogen we see that energy use can grow at 0.5%, 1.0%, or 1.5% for 562, 287, or 191 years beyond 2000. At these times total energy use will be 220, 224 or 231 TW.

If fossil fuel use is limited to 9 TW, the 7500 TWy of available fossil fuels would last for about 833 years. If nuclear fuel is limited to 3, 7 or 14 TW it would last for 333, 143 or 71 years if used in conventional fission reactors, or for 20,000, 8,600 or 4,300 years if used in breeders.

If land use for photovoltaic hydrogen is limited to 2%, total energy use is limited to about 60TW, and some alternative energy source will need to be found for the 3, 7 or 14 TW produced by nuclear fuel, if it is used for conventional reactors, after 333, 143 or 71 years. If no alternatives are available then total energy use would have to be reduced to about 57, 53, or 46 TW. After another 800 years additional energy sources would need to be available for the 9 TW supplied by fossil fuels. If no alternatives are available then total energy use would have to be reduced further, to 48, 44 or 37 TW. If the nuclear fuel is used for breeders no alternative sources would be needed before 4300 years at the earliest.

If land use for photovoltaic hydrogen is limited to 12% total energy use will be limited to about 220 TW, and if no alternative is found for the portion supplied by (conventional) nuclear power, total energy use will have to be reduced to about 217, 213 or 206 TW after 333, 143 or 71 years. After another 800 years these levels would need to be reduced to 208, 204, or 197 TW if no substitute for the 9 TW supplied by fossil fuels is found. If we are comfortable using the nuclear fuel in breeder reactors no alternative sources would be needed before less than 4300 years.

Summary

1. If fusion is practicable, there appears to be no reason that energy use cannot continue to grow until it reaches the 5400 TW limit imposed by thermal pollution. This is about 415 times the level of energy use today. This level will be reached in about 300 years if energy use grows rapidly (1.5% per year), and 1000 years if it grows slowly (0.5%). It would be sustainable for perhaps 20,000 to 200,000 years after that.

2. If fusion is not practicable then photovoltaic hydrogen is an alternative. If we are able to use 12% of land surface for photovoltaic hydrogen then energy use will be able to grow until it reaches 220 TW, about 17 times today's level. This level will be reached in about 200 years if we grow rapidly and 500 years if we grow slowly. If we can only use 2% of the land for photovoltaic hydrogen we will be limited to about 60 TW, which is 4.6 times today's level, and would be reached in about 100 years if we grow rapidly and 270 years if we grow slowly.

3. In the two scenarios above fossil and nuclear fuels serve as transitional sources of energy. If neither fusion nor photovoltaic hydrogen are practicable then heavy reliance on breeders would allow us to grow slowly for perhaps 600 years (to a level of 300 TW), or rapidly for 300 years (to 1000 TW). But by the end of these periods we would need to have found substitutes or face catastrophic collapse. Available substitutes such as biomass and other renewables have practicable limits that total in the neighborhood of 33 TW. If we are willing to employ breeder technology we could grow at slow or moderate rates for 200 or 300 years and see if some exotic energy sources might be made practicable; if this does not happen we would have another 200 to 300 years to make a transition to a 33 TW world based on biomass and other renewables.

4. If neither fusion nor photovoltaic hydrogen are practicable and we are not willing to employ breeders then we can grow until we reach the 33 TW level that is sustainable with biomass and other renewables. This will happen in about 60 years if we grow rapidly or 180 years if we grow slowly. The fossil fuel share of total energy use is limited to 9 TW, so in the near

term most new energy would be supplied by nuclear fission. Fission sources could be phased out as biomass sources are established. A 33 TW biomass/renewables world would be sustainable as long as the sun shines.

Assessment

What are we to make of these scenarios? A person who expects fusion and large-scale photovoltaic hydrogen to be practicable and socially acceptable might note that combinations of these could comfortably allow energy use to grow at moderate rates for another 400 to 600 years before any biogeophysical limits are encountered; that at a minimum these limits would still represent a 20-fold increase over today's level of energy use; and that these levels would be sustainable for at least tens of thousands of years (if we relied mostly on fusion) and perhaps for as long as the sun shines (if we relied mostly on photovoltaic hydrogen).

A person inclined to be cautious about these matters might judge that since the practicability of fusion is unknown, and since the full impacts of covering 12% of the earth's land area with photocells are likely to entail unacceptable social costs, and since breeder technologies should be rejected from the start, the only scenario about which we can feel reasonably confident is the one in which global energy use reaches its highest practicable, sustainable level at about 60 TW of mostly photovoltaic hydrogen power, using 2% of the land area, sometime within the next 100 to 270 years. This scenario would likely employ biomass and other renewables as well.

Thus a "moderate techno-optimist" might judge that energy use can continue to grow for perhaps 400 to 600 years, until it reaches a sustainable level 20 times today's level; while a "moderate techno-skeptic" might judge that energy use can grow for maybe 100 to 270 years, until it reaches a sustainable level perhaps 5 times as high as today's.

II.A.2.b. Catastrophic Global Warming

Is global warming a limit to growth? Is it possible that continued warming might trigger a biogeophysical catastrophe of such magnitude that economic growth could no longer be sustained?

The integrated assessment models used to study the impacts of global warming generally model damages as smoothly increasing exponential functions of atmospheric warming. An example is Nordhaus' "high estimate" damage function, discussed below. It suggests that a 2.5°C warming might reduce GDP by as much as 2.2% below what it otherwise would have been, that a 4°C warming would reduce GDP by as much as 5.7%, and so on.

However, the fact that these models do not show abrupt climate change, and that the level of damages they show is generally modest, at least for warming levels expected over the next 100-200 years, is as much an expression of our ignorance as it is of our expertise. Because the stakes are so high, most analysts agree that the continued study of possible catastrophic impacts of global warming is a high research priority.

Box IIA-18 lists some of the events that might be triggered by continued global warming and have truly catastrophic impacts. **IIA-19** describes three of these in more detail.

Lempert et al. (1994) conducted one of the few detailed evaluations of potentially catastrophic climate change events. They considered four of the possible events listed in Box IIA-18: collapse of the thermohaline circulation, methane release, saturation of CO2 sinks, and sudden changes in climate sensitivity. In each case they figured conservatively that the abrupt change would be triggered when atmospheric warming exceeded 1.5° C.

Box IIA-20 shows the results of their calculations. While these events do increase the rate of atmospheric warming, their impacts are not especially dramatic, with the exception of event (iv) where the overall sensitivity of the climatic system to greenhouse gas concentrations suddenly doubles. Event (iv), however, is a "dummy" event for which no particular driving mechanism is suggested. On the other hand, each of the scenarios tested assumes that the 1.5° C

BOX IIA-18. POSSIBLE CATASTROPHIC CLIMATE CHANGE EVENTS

[major source: IPCC Working Group III, 1996]

I. Runaway greenhouse effect, due to:

- a) Rapid increases in greenhouse gas emissions, due to:
  - i) destabilization of methane clathrates
  - ii) melting of permafrost and revival of metabolism of sub-surface organic deposits
- b) Shutdown of major greenhouse gas sinks, due to:
  - i) decreased planktonic activity
  - ii) a slowdown in the growth of forests
  - iii) a die-back of forests
- c) Changes in atmospheric chemistry

II. Disintegration of the West Antarctic Ice Sheet (WAIS)

III. Collapse of the North Atlantic thermohaline circulation

IV. Unknown mechanisms

BOX IIA-19. THREE POSSIBLE CATASTROPHIC CLIMATE CHANGE EVENTS

1. Methane Clathrates

Methane clathrates are ice-lattice structures with a molecule of methane trapped within them. It is estimated that perhaps 11,000 Gt of carbon lie trapped along the continental shelves in the form of methane clathrates. If ocean waters warm due to climate change these structures could become unstable. Enormous quantities of methane, which as a greenhouse gas is ten times more potent than CO2, could escape into the atmosphere and lead to an abrupt rise in global temperature.

Kvenholden (1988) estimated that destabilization of the off-shore clathrates could generate methane emissions of 120 Mt/yr. Lashoff (1989) estimated that a 1 degree warming at the water-sediment interface could generate methane emissions of 220 Mt/yr. This would be sufficient to increase the warming generated by a doubling of CO2 concentrations from 2.5 ^{0}C to 3 ^{0}C, in a very short period of time.

2. Collapse of the North Atlantic Thermohaline Circulation.

Differences in atmospheric temperature are primary drivers of ocean circulation. Warm Gulf Stream waters travel north and become cooler, and thus denser, when they reach the North Atlantic. These waters release their heat and sink, and become part of the deep ocean current that travels south through the Atlantic and around the tip of Africa. As the earth's atmosphere warms northern polar ice is expected to melt and release fresh water into the North Atlantic. Because fresh water is less dense than salt water, this release is expected to weaken the thermohaline circulation. As a result temperatures in much of Northern Europe could drop dramatically. Other ocean-atmosphere phenomena, such as the Asian Monsoon, could be affected as well.

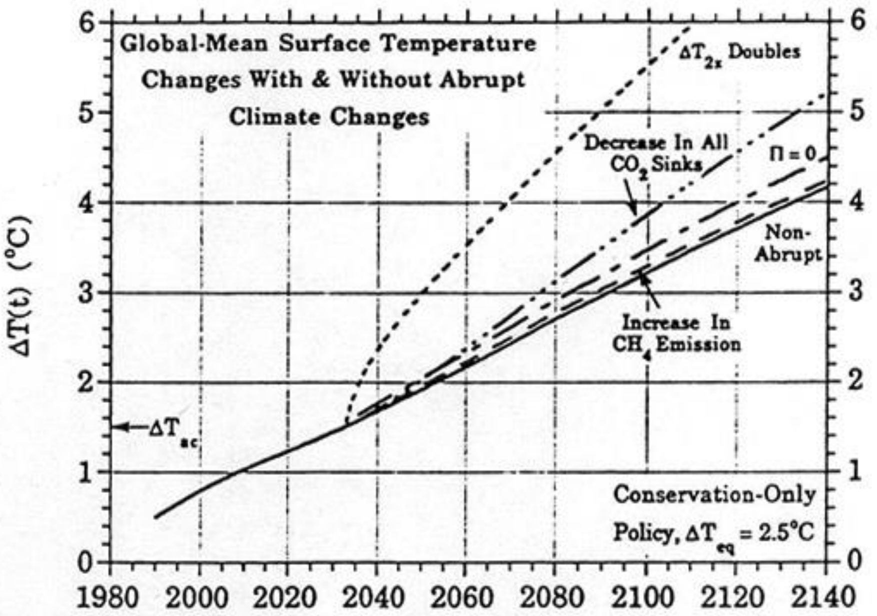
Manabe and Stouffer (1993) showed that under a 2x CO2 warming the intensity of the thermohaline circulation could be reduce by over 50%, although over time it would re-establish itself. But if the concentration of atmospheric CO2 were allowed to rise to 4 times its pre-industrial level, the thermohaline circulation would drop almost to zero, and there establish a new stable equilibrium.

3. Disintegration of the West Antarctic Ice Sheet (WAIS)

The West Antarctic Ice Sheet rests on solid rock and flows towards the sea, but is held back by the large ice flows that extend across the ocean surface. If these ice flows melt due to global warming, the WAIS could surge into the ocean and increase sea levels by as much as 20 feet. Cline (1993) suggests that this could become a threat when global warming begins to exceed 7^0 C. Some authors suggest that the East Antarctic Ice Sheet would be vulnerable as well, and alone could raise sea levels by 50 feet.

BOX IIA-20. Impact on Atmospheric Warming of Abrupt Climate Change

[reprinted from Lempert et al 1994]



Annual global-mean surface temperature change, $\Delta T(t)$, for Conservation-Only policy and $\Delta T_{2x} = 2.5$ °C for: (a) non-abrupt climate change; and (b) for abrupt change at $\Delta T(t) = 1.5$ °C consisting of: (i) decrease in all CO_2 sinks; (ii) increase in CH_4 sources; (iii) decrease in ocean polar heat transport parameter, Π; or (iv) doubling of climate sensitivity to $\Delta T_{2x} = 5.0$ °C.

warming would trigger only a single event. But there is no reason that several or all of the abrupt events could not be triggered simultaneously.

Suppose we found strong evidence of a biogeophysical mechanism that would be triggered by some predictable degree of warming and would truly cause a global catastrophe that would bring economic growth to an end. The important question then becomes, what are our options? Can technological fixes eliminate the threat at little cost, or maybe even generate some net benefits? Or--at the other extreme--would we need to abandon our industrial modes of production and return to a world of small scale agrarian communities?

Boxes IIA-21 and **IIA-22** show the results of an exercise I conducted that incorporates a truly catastrophic damage function into Nordhaus' DICE model.[10] This function shows damages increasing with the 12th power of warming, once warming exceeds the critical threshold of 2.5°C.

When the model is run to get the optimal solution we find that catastrophe can be avoided if over the next century we begin and complete a transition away from a fossil fuel based economy. In absolute terms this is a costly process. Figure 4 in IIA-22 shows that we would have to sacrifice about 6% of the level of global output that we would have been capable of producing had global warming not been a problem. But notice that over the entire trajectory of this transformation economic growth continues to be positive. Output still grows, although at a (marginally) slower rate. At each point in time we are economically more prosperous than ever. By 2200 per capita GDP is 3.2 times larger than it was in 1994.[11]

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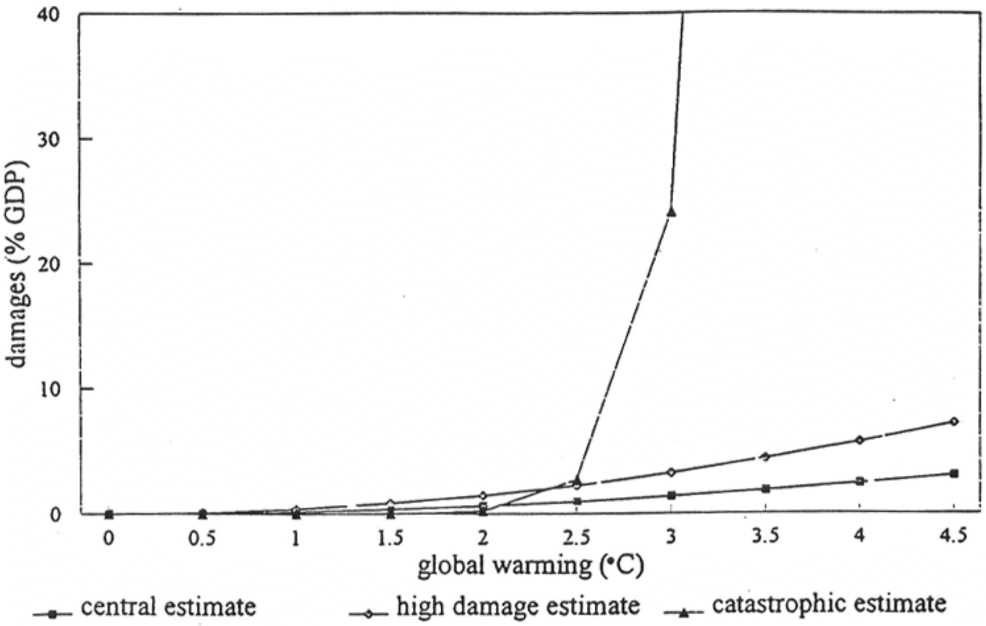
[10] The DICE computer model was kindly made available by Dr. Nordhaus. I ran it using GAMS software made available by the U.C. Berkeley Department of Natural Resources.

[11] Two caveats should be noted. Nordhaus' model does not specify the particular mix of energy technologies that would allow us to move off fossil fuels at a cost of 6% of GDP, but the studies on which his estimates are based typically rely heavily on nuclear power. A scenario that emphasized non-nuclear options might be more costly. On the other hand, it might not. Nordhaus' DICE model does not allow for the possibility—many would say likelihood—that the cost of alternative energy resources will decline over time due to technological development. In that event the cost of a transition away from fossil fuels might be even less than 6%.

BOX IIA-21. DAMAGES FROM GLOBAL WARMING

Figure 1 shows estimates of the extent of damages that might be expected if atmospheric warming increase to the levels shown, using Nordhaus' DICE model (1994) on GAMS software. Damages are defined as the amount of output (GDP) that is lost due to climate change, measured as a percentage of the level of GDP that would have been realized in the absence of climate change.

Figure 1. Damages from Global Warming



Central estimate damage function: $d = .013\left(\frac{\Delta T}{3}\right)^{2}$

High estimate damage function: $d = .032\left(\frac{\Delta T}{3}\right)^{2}$

Catastrophic damage function: $d = .027\left(\frac{\Delta T}{2.5}\right)^{12}$

BOX IIA-22. THE ECONOMICS OF CATASTROPHIC GLOBAL WARMING

Figures 1 through 4 show optimal trajectories of atmospheric warming, CO2 emissions, damages and GDP generated by Nordhaus' DICE model (1994) using the central and catastrophic damage functions shown in Box IIA-21.

Figure 1. Reduction of CO2 Emissions

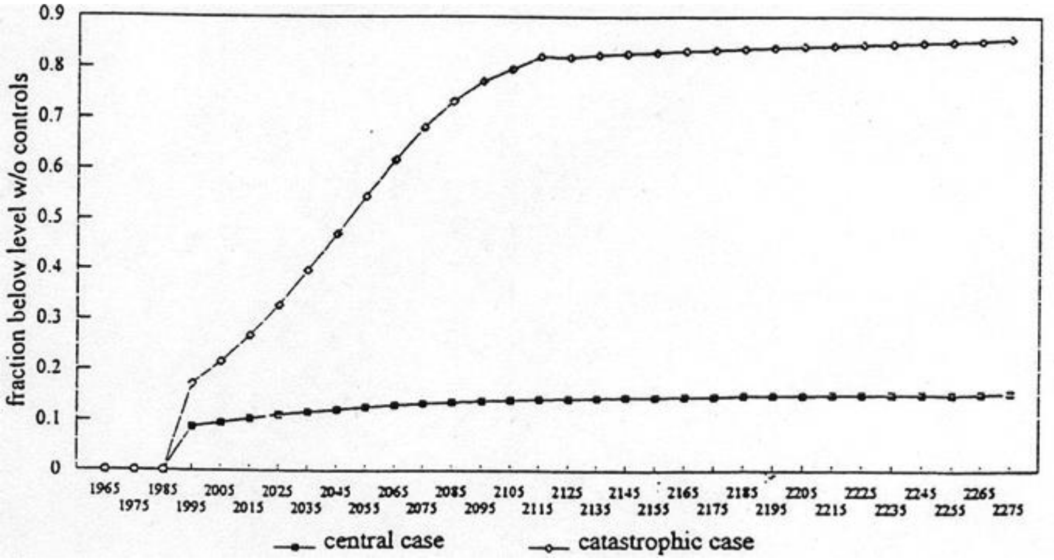
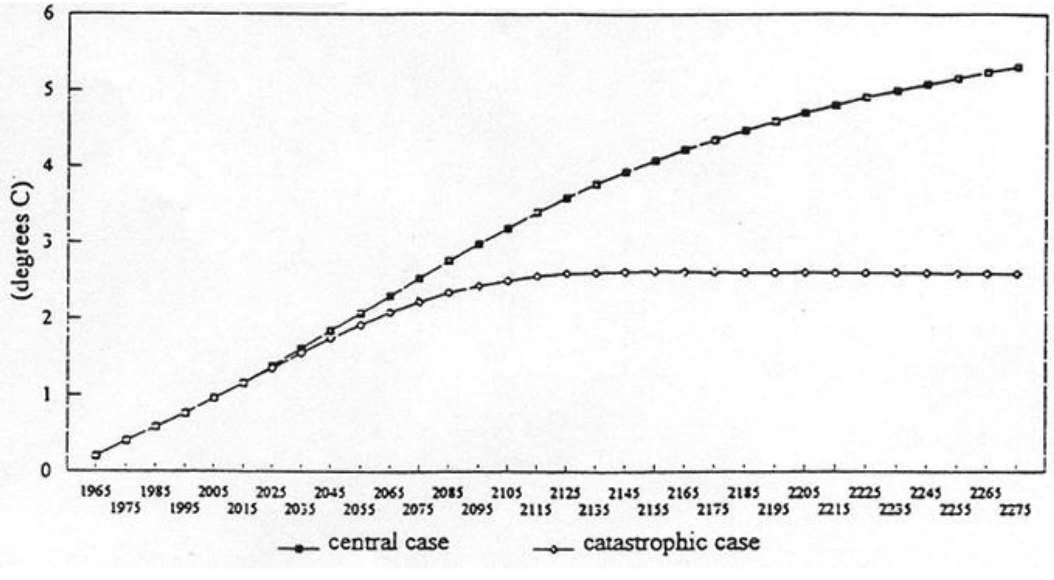


Figure 2. Atmospheric Warming



[more….]

BOX IIA-22. The Economics of Catastrophic Global Warming (cont'd.)

(Figures 1 through 4 show optimal trajectories of atmospheric warming, CO2 emissions, damages and GDP generated by Nordhaus' DICE model (1994) using the central and catastrophic damage functions shown in Box IIA-21.)

Figure 3. Damages from Global Warming

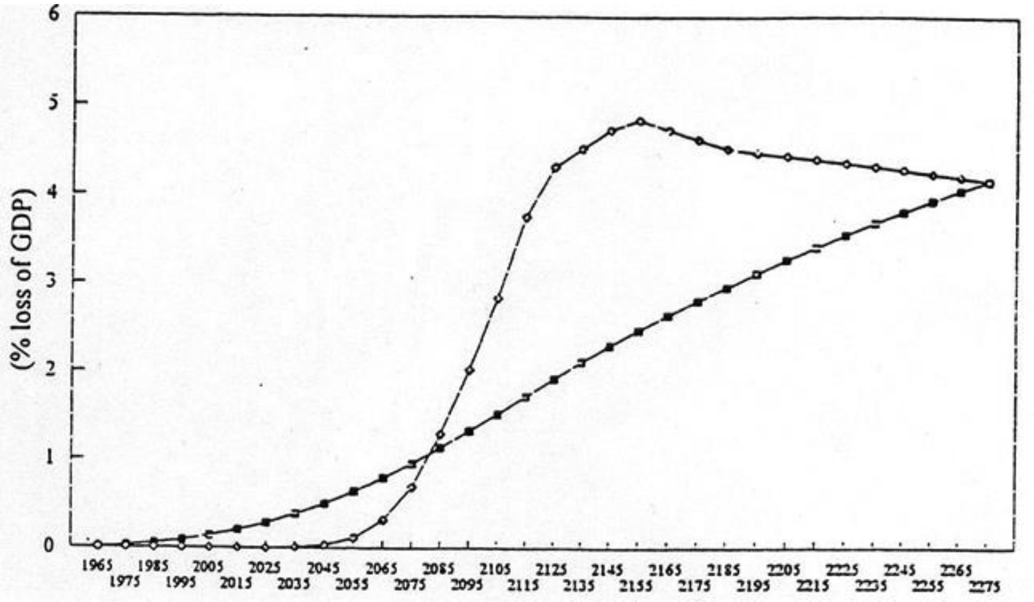
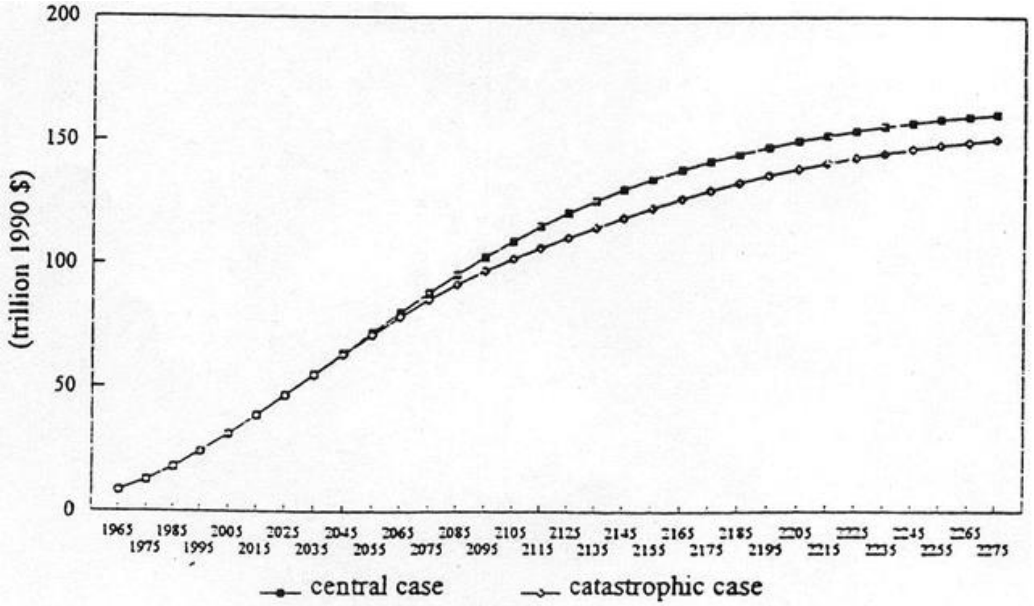


Figure 4. World Output (GDP)



II.A.2.c. Other Biogeophysical Limits

In *The Case That the World Has Reached Limits*, Goodland (1991) offers five main signs "that the limits have been reached." These are: human biomass appropriation, global warming, ozone shield rupture, land degradation and decrease in biodiversity. Daly (1989) and others cite entropic degradation as an additional limit to growth. We saw in II.A.2.b that unacceptable global warming can be avoided without having to bring an end to the growth of economic output. While ozone shield rupture, land degradation and biodiversity loss are serious concerns, it does not appear that the policies necessary to successfully address them require that economic growth come to an end. Here we comment briefly on entropy and the appropriation of biomass:

1. Entropy

The second law of thermodynamics, also known as the Entropy Law, states that in a closed system the available energy, although conserved, necessarily converts from more ordered, "low entropy" forms, to less ordered, "high entropy" forms. The electromagnetic energy carried in the molecular bonds of a lump of coal is more "ordered" than is the kinetic energy carried by the surrounding air molecules after the coal has been burned. Because of this inevitable and continual degradation, energy becomes less able to do useful work, and recycling of materials can never be 100% effective.

Georgescu-Roegen (1971) uses the second law of thermodynamics to argue that economic growth cannot continue indefinitely; indeed, that even a steady-state level of output is unsustainable. As stated this is strictly correct. But the important question then becomes: how long do we have before entropic limits are felt? Solar radiation will provide the earth with a steady input of high-quality (low entropy) energy for as long as the sun shines—perhaps another 6 billion years. The entropic degradation of energy resources will not be a real limit to growth anytime within that period. (Of course, the growth of solar energy use *is* limited by the area of the land available for solar energy collectors, as we just saw.)

2. Human Appropriation of the Products of Photosynthesis

Net Primary Productivity is the energy stored in plants. It is the base of the food chain for nearly all life on earth. Vitousek et al (1986) found that 40% of Net Primary Productivity is currently being "appropriated" for human use. This finding has been interpreted to imply that the human population can increase by, at most, 1.5 times its current level. It has also been interpreted an indicator of near-term limits to the growth of human activity on earth in general (Goodland, 1996).

These interpretations are misleading. The 40% figure does give some insight concerning the extent to which human activity has probably caused changes in patterns of land use over the course of history. But it says little about limits to the growth of population or economic activity. The resource that generates Net Primary Productivity is solar energy. The total solar flux reaching the continental land masses is about 25,000 TW. This is 370 times the 68 TW that is currently embodied in NNP. Food supply for humans can be increased by "appropriating" more of the solar flux, e.g., by increasing the productivity of existing agricultural lands, or by bringing new land into agricultural uses. At the same time energy for continued economic growth is available from many sources other than biomass.

II.A.2.d. Integrated Assessment of Climate Change

Interest in long range global models of environmental and economic change waned after the mid-1970's but revived in the late 1980's in the wake of heightened concern about global warming. Policy makers wanted to know how bad warming might be, what damages it might cause, what preventive measures were available, and what these would cost. Answers required analytic models that included the many indirect and reciprocal influences that economic, climatic, ecological, demographic and other factors could have upon one another. These are now called integrated assessment models. The key components of a typical integrated assessment model of climate change are shown in **IIA-23.** A classification of integrated assessment models is shown in **IIA-24**. A generalized model is described in **IIA-25**.

None of the many scenarios studied in the course of work with the integrated assessment models have as yet suggested mechanisms that lead to global economic or environmental collapse, in the manner depicted by World 3, over the course of the next 200 years or so.[12]

On the other hand, the reference scenarios chosen for these models do show a generally steady decline in the rate of economic growth over time. This can be seen in the output trajectories for Nordhaus' RICE model shown in IA-6, in the growth paths used by the Energy Modeling Forum shown in **IIA-26**, and in many other studies.

What explanation is given for this? Generally very little. Among the few authors who motivate their reference scenario growth assumptions is Nordhaus (1992), who attributes it to the onset of diminishing returns to productivity-enhancing technological innovation.

It remains to be seen whether more ambitious efforts to model linkages among biogeophysical processes and economic activity might reveal mechanisms that could bring economic growth to an end. But if the reference scenarios of the integrated assessment models are correct then economic growth might be expected to come to an end in any event—not because of resource depletion or biogeophysical catastrophe, but because of limits to technological innovation.

What are the grounds for such a belief? We discuss this question in the next section.

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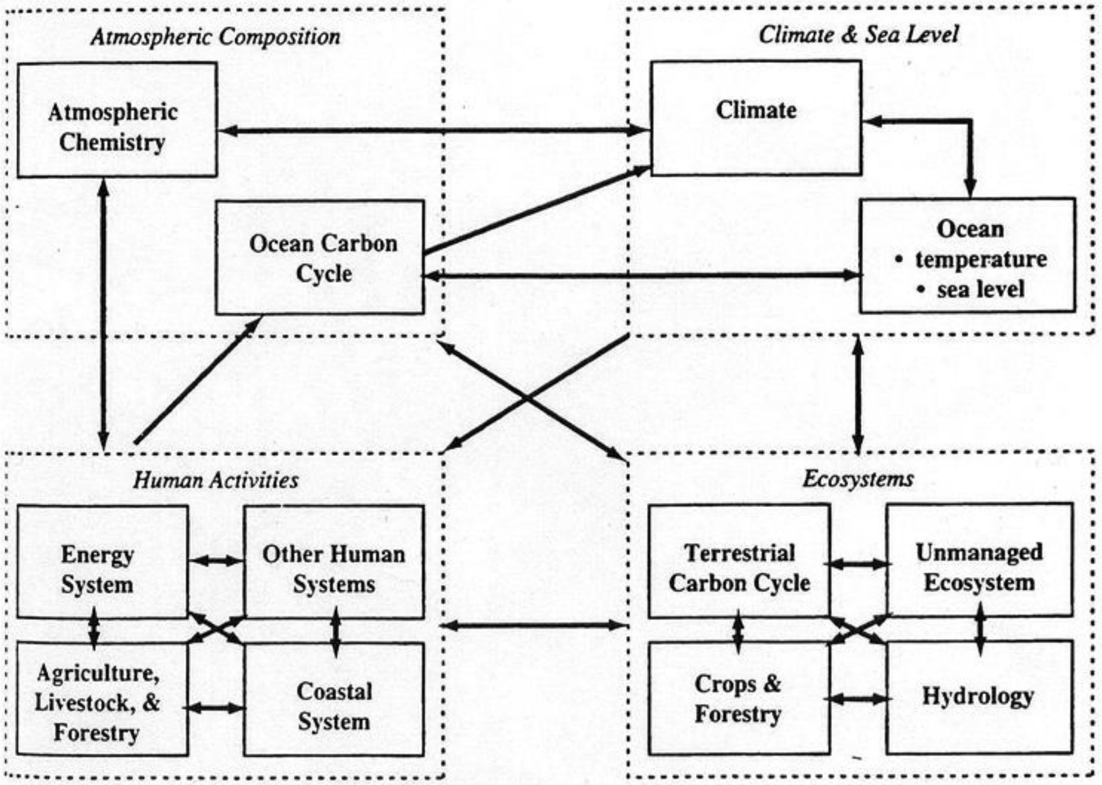
[12] It's important to note, however, that many of the more simple integrated assessment models are constructed in a way that precludes economic collapse. They model on-going output growth as an exogenous assumption, and measure damages as simple percentage reductions from this level of growing output.

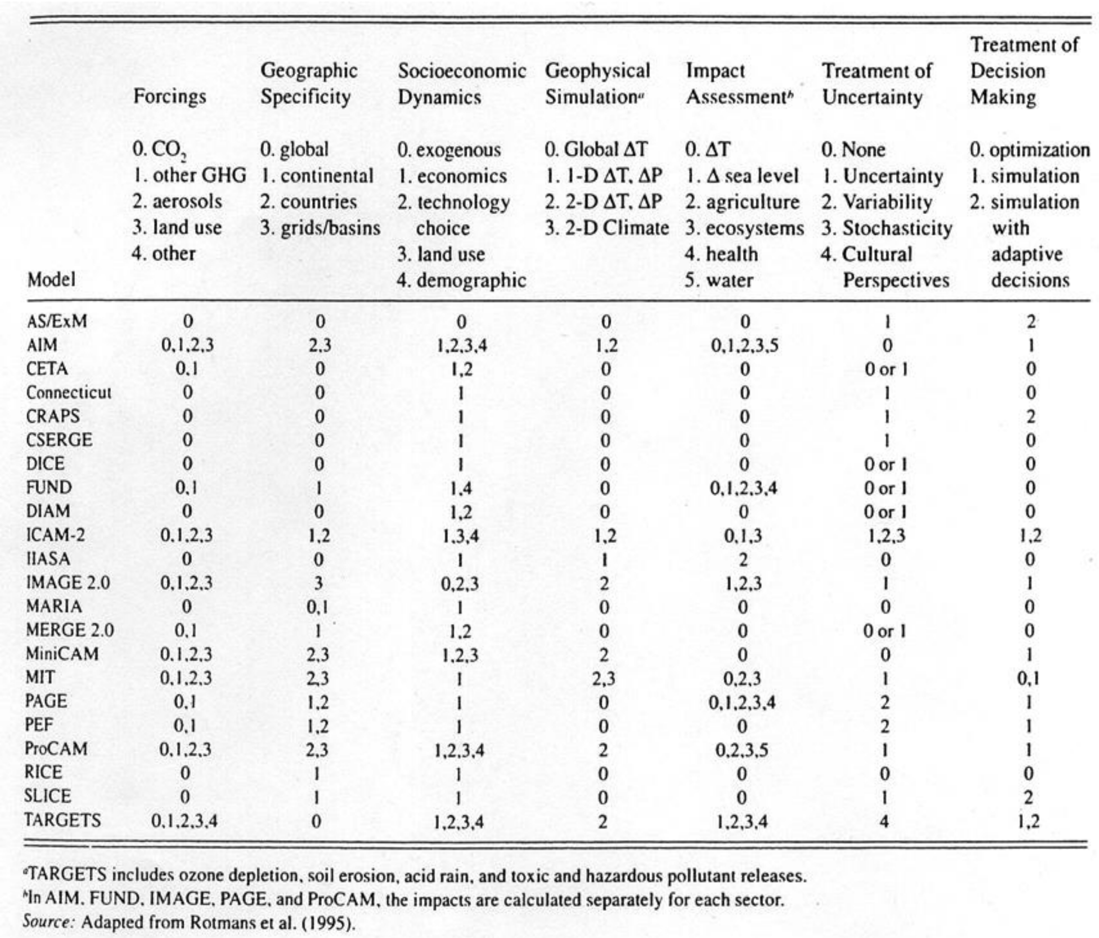
BOX IIA-23. KEY COMPONENTS OF FULL-SCALE INTEGRATED ASSESSMENT MODELS

[Reprinted from IPCC, Climate Change 1995: Economic and Social Dimensions of Climate Change (1996)].



BOX IIA-24. Summary Characterization of Integrated Assessment Models

[Reprinted from IPCC, Climate Change 1995: Economic and Social Dimensions of Climate Change (1996)].



Model	Forcings 0. CO_2 1. other GHG 2. aerosols 3. land use 4. other	Geographic Specificity 0. global 1. continental 2. countries 3. grids/basins	Socioeconomic Dynamics 0. exogenous 1. economics 2. technology choice 3. land use 4. demographic	Geophysical Simulation[a] 0. Global ΔT 1. 1-D ΔT, ΔP 2. 2-D ΔT, ΔP 3. 2-D Climate	Impact Assessment[b] 0. ΔT 1. Δ sea level 2. agriculture 3. ecosystems 4. health 5. water	Treatment of Uncertainty 0. None 1. Uncertainty 2. Variability 3. Stochasticity 4. Cultural Perspectives	Treatment of Decision Making 0. optimization 1. simulation 2. simulation with adaptive decisions
AS/ExM	0	0	0	0	0	1	2
AIM	0,1,2,3	2,3	1,2,3,4	1,2	0,1,2,3,5	0	1
CETA	0,1	0	1,2	0	0	0 or 1	0
Connecticut	0	0	1	0	0	1	0
CRAPS	0	0	1	0	0	1	2
CSERGE	0	0	1	0	0	1	0
DICE	0	0	1	0	0	0 or 1	0
FUND	0,1	1	1,4	0	0,1,2,3,4	0 or 1	0
DIAM	0	0	1,2	0	0	0 or 1	0
ICAM-2	0,1,2,3	1,2	1,3,4	1,2	0,1,3	1,2,3	1,2
IIASA	0	0	1	1	2	0	0
IMAGE 2.0	0,1,2,3	3	0,2,3	2	1,2,3	1	1
MARIA	0	0,1	1	0	0	0	0
MERGE 2.0	0,1	1	1,2	0	0	0 or 1	0
MiniCAM	0,1,2,3	2,3	1,2,3	2	0	0	1
MIT	0,1,2,3	2,3	1	2,3	0,2,3	1	0,1
PAGE	0,1	1,2	1	0	0,1,2,3,4	2	1
PEF	0,1	1,2	1	0	0	2	1
ProCAM	0,1,2,3	2,3	1,2,3,4	2	0,2,3,5	1	1
RICE	0	1	1	0	0	0	0
SLICE	0	1	1	0	0	1	2
TARGETS	0,1,2,3,4	0	1,2,3,4	2	1,2,3,4	4	1,2

[a] TARGETS includes ozone depletion, soil erosion, acid rain, and toxic and hazardous pollutant releases.

[b] In AIM, FUND, IMAGE, PAGE, and ProCAM, the impacts are calculated separately for each sector.

Source: Adapted from Rotmans et al. (1995).

BOX IIA-25. A Generalized Integrated Assessment Model

These equations represent the core elements of a typical integrated assessment model.

1) Output $Y = \Omega A K^{\alpha} L^{\beta}$

2) Population $\dot{L} = nL$

3) Technology $\dot{A} = g A$

4) Capital $\dot{K} = sY - \delta K$

5) "Pollution" $P = \theta_1 Y^{\theta_2}$

6) Environmental Damage $D = \phi_1 P^{\phi_2}$

7) Costs of "Pollution" Abatement $TC = \sigma_1 \mu^{\sigma_2}$

8) Impact of Damages and Abatement on Output $\Omega = \left(\frac{1 - TC}{1 + D} \right)$

Definitions of parameters:

α, β	elasticities of output with respect to capital and labor
n	population growth rate
g	productivity growth rate
s	savings rate
δ	depreciation rate of capital
θ_1, θ_2	proportional and scale constants relating pollution to output
ϕ_1, ϕ_2	proportional and scale constants relating damages to pollution
μ	degree of pollution abatement desired ($0 < \mu < 1$)
σ_1, σ_2	proportional and scale constants relating cost of abatement to the degree of pollution abatement desired

BOX IIA-26. Projected Changes in Productivity, 2000-2200

[source: Energy Modeling Forum 12, 1996]